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Automated Inspection of Aircraft

June 1996

Final Report

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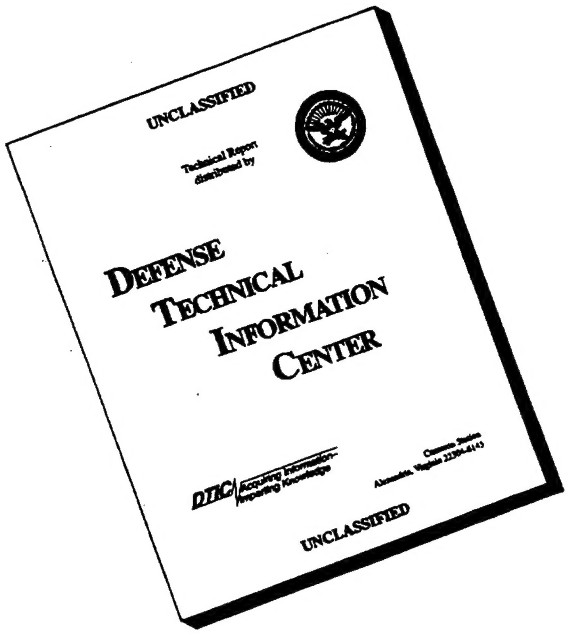

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16. Abstract

This report describes the development of a robotic system designed to assist aircraft inspectors by remotely deploying nondestructive inspection (NDI) sensors and acquiring, processing, and storing inspection data.

During a preliminary phase of work under this program, Carnegie Mellon University studied the task of aircraft inspection, compiled the functional requirements for an automated system to inspect skin fastener rows, and developed a conceptual design of an inspection robot. A prototype of the robotic inspection system (the Automated NonDestructive Inspector or ANDI) has been developed. The first phase of system development resulted in a laboratory system that was able to demonstrate the abilities to adhere to the surface of an aircraft panel and to deploy a standard eddy-current sensor.

This report describes the most recent developments in the program. The major accomplishments of the phase include: Enhancing the mechanics, adding video cameras to the robot for navigation, adding an onboard computer for low-level task sequencing, and demonstrating the system at the FAA's Aging Aircraft NDI Validation Center (AANC) during the 1994 Air Transport Association NDT Forum.

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EXECUTIVE SUMMARY

Carnegie Mellon University (CMU) is conducting a research program for the Federal Aviation Administration's (FAA) National Aging Aircraft Research Program to develop robotic tools to assist aircraft inspectors by automating the collection, archiving, and post-processing of inspection data. The results of this program will establish the technical feasibility of using robotic nondestructive inspection (NDI) systems in major aircraft maintenance facilities. This program has been funded through the William J. Hughes Technical Center. USAir is supporting the project by providing technical guidance from experienced aircraft inspectors and access to aircraft in its Pittsburgh, PA, maintenance facilities.

During a preliminary phase of work under this program, CMU studied the task of aircraft inspection, compiled the functional requirements for an automated system to inspect skin fastener rows, and developed a conceptual design of an inspection robot. The purpose of this robotic system was to automatically deploy conventional sensors used by aircraft inspectors. The system was designed to be sufficiently flexible to allow for the incorporation of new sensor technologies, including those being developed by other organizations participating in the FAA's National Aging Aircraft Research Program.

A prototype of the robotic inspection system, (the Automated Nondestructive Inspector or ANDI), has been developed. The first phase of system development resulted in a laboratory system that demonstrated the ability to adhere to the surface of an aircraft panel and deploy a standard eddy-current sensor. Results of the first phase are documented in report DOT/FAA/CT-94/23, June 1994.

This report describes the most recent developments in the program, covering the period from January 1993 through June 1995. The major accomplishments of this phase of the project are:

- The mechanics of the inspection robot have been enhanced for mobility around the circumference of the fuselage.
- Video cameras have been added to the robot to enable remote, and eventually automated, navigation.
- An onboard computer has been added to the robot for sequencing low-level tasks, such as actuating cylinders.
- Software to control the eddy-current system remotely has been integrated with the system.
- Communication between the ground and onboard computers has been installed.
- The capability to overlay a wireframe model of the robot over selected aircraft models was added to the operator interface to provide graphical navigational information to the inspector.
- Automatic alignment algorithms have been developed and tested under laboratory conditions. These algorithms have not yet been integrated with the system.
- The robot was deployed and demonstrated during the 1994 Air Transport Association (ATA) NDT Forum hosted by the FAA's Aging Aircraft NDI Validation Center operated by Sandia National Laboratories in Albuquerque, New Mexico.

Several operational limitations of the robotic inspection system were exposed during the laboratory testing and field demonstration. Specific problems include this prototype robot's

speed, absence of a high-level of operator control, and mechanical reliability. As a result of these experiments, insight has been gained into means for improving speed, ease of operation, and mechanical performance. Future development efforts will be directed towards obtaining more autonomous robot operation by providing higher level operator controls.

1. INTRODUCTION

Carnegie Mellon University (CMU) is conducting a research program for the Federal Aviation Administration's (FAA) National Aging Aircraft Research Program to develop robotic tools to assist aircraft inspectors by automating the collection, archiving, and post-processing of inspection data. The results of this project will establish the technical feasibility of using robotic systems in aircraft maintenance facilities. Operational and economic issues associated with robotic inspection of aircraft are beyond the scope of this project.

1.1 Background

1.1.1 Envisioned Inspection System

In the preliminary phase of this project, a conceptual design of a robotic aircraft inspection system was developed. The task of aircraft skin inspection was selected as the first application to be automated because the airline industry indicated a preference for automation of this function. The task is to look for small cracks around fasteners due to stress fatigue as well as for thinning of the skin due to corrosion. Searching for such flaws is a highly repetitive task that may lead to a reduced probability of detection of defects due to inspector fatigue or boredom.

The emphasis of this effort was to design a system that would assist, rather than replace, aircraft inspectors. The inspection tasks would be divided between the human inspector and the robot. The automated system would deploy the sensors in a consistent manner and process sensor signals for any abnormal indications while the inspectors would monitor the system and would be required to make final judgments on unusual sensor readings.

The design goals for the system were:

- Modular - Both the hardware and software for the system would be modular, allowing for relatively easy changes to the system.
- Extensible - The system would be designed to allow other modules to be added to the basic architecture as needed, thus extending the system's capabilities.
- Easy to use - To be of benefit to the user community, the system would have to be easy for users to operate.
- Computer platform independence - Multiple organizations will have a variety of computing hardware requirements. Thus, the system would have to be functional across a variety of computer platforms.
- LAN aware - Because airlines have distributed inspection centers, information must be shared within a specific inspection facility as well as across inspection facilities. Tying the systems to a local area network (LAN) would provide this capability.

Work on the preliminary phase of this project to develop a conceptual design of an automated aircraft inspection system was initiated in May 1991. The initial work comprised reviewing airline inspection procedures and state-of-the-art robotics technology and creating a conceptual design of a system called the Automated Nondestructive Inspector, ANDI. This was completed in December, 1991. The basic design of the robot consisted of the following elements [1]:

- Mechanical System - The mechanical device was envisioned as a cruciform robot that would adhere to the aircraft fuselage using suction cups.

- Control System - Based on the map of a specific aircraft contained in the database and the inspection to be performed, the control software would generate a path for the robot to follow. The control software would also control the movements of the electro-mechanical hardware.
- Data Management System - Information on the types and locations of abnormal sensor signals would be stored in a database. The database would contain a map of the surface of each type of aircraft. Each specific aircraft would have an inspection record that would describe and map the locations of repairs and possible flaws. The system would gather inspection data and store it locally. This data would be shared with the entire maintenance facility as well as with all of the carrier's maintenance facilities nationwide.
- Sensors - The robot would deploy eddy-current sensors on the skin to test for surface and subsurface cracks and/or corrosion which causes thinning of material. Small onboard cameras focusing on the fuselage surface would provide the inspector with images of the skin and would be used for robot navigation.
- Human-Machine Interface - This would comprise the following elements: video monitors, teleoperation controls, and a workstation with graphics capabilities.

Figure 1 depicts the system architecture which was envisioned in the preliminary phase of work.

The envisioned system architecture was a complex one which divided the tasks among several ground-based computers and an onboard computer. The ground-based processors would control the major system tasks, such as database acquisition, robot control, and sensor signal processing. The onboard processor would control the onboard hardware and the sequencing of tasks. Some of the highlights of the envisioned system architecture were:

- interprocess communications between multiple ground based computers through local area network (LAN)
- additional, special purpose operator interfaces
- prototype inspection, aircraft, and maintenance databases
- video for close-up rivet inspection and wide angle robot/aircraft monitoring
- lights and illumination control for onboard video
- additional robot sensors, i.e., end of motor travel (EOT) and collision detection

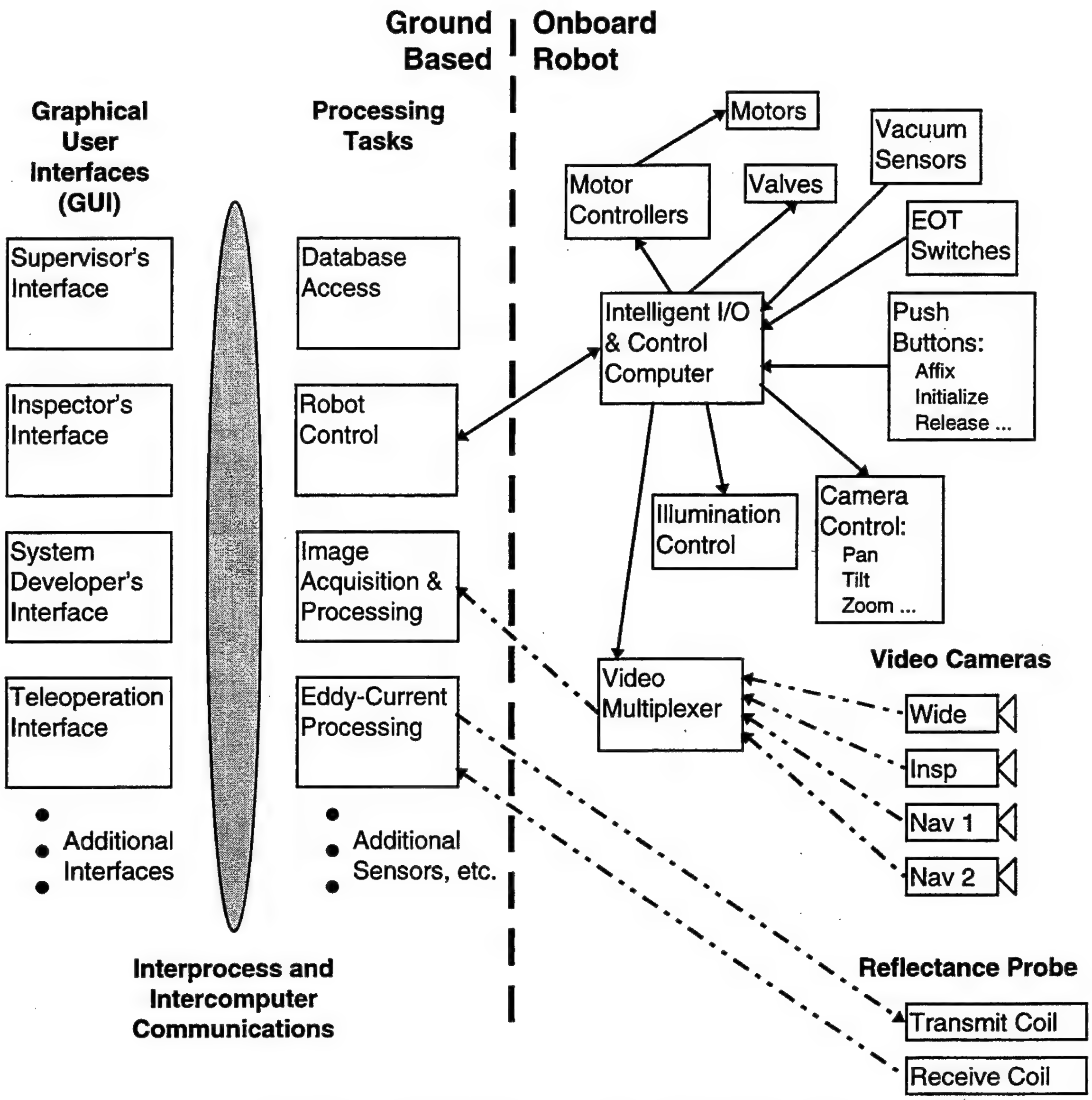

FIGURE 1. ENVISIONED SYSTEM ARCHITECTURE

1.1.2 Early Prototype Inspection System

The conceptual design which was specified in the preliminary phase of work described a very robust inspection system. The strategy employed by CMU was to approach the system development in phases; the product of each phase would be a system with a useful subset of the complete system's capabilities. In addition, each system would be upwardly compatible with subsequent systems.

Work building a prototype of the cruciform robot design and developing software to support its motion began May 1992. This was completed in January 1993. The accomplishments in this phase were [2]:

- Mechanical System - The first prototype of the robotic system was developed and tested. The prototype weighed approximately 30 pounds (14 kg), and was able to adhere to a surface and perform a scan.

- Control System - The development of the control software was initiated in this development phase. The software controlled the scanning and walking motions of the mechanical device.
- Data Management System - The inspection data acquisition and analysis functions used by the system during this phase were those available in a commercial eddy-current system.
- Sensors - The mechanical device deployed a commonly used sliding eddy-current sensor over a row of fasteners. In addition, experimentation with video cameras began, and a video specification document was written.
- Human-Machine Interface - The system functions were controlled by a personal computer (PC) workstation. A simple menu-driven interface was provided for the operator. The output from the commercial eddy-current system was shown on a second monitor.

As shown in Figure 2, one ground-based PC controlled the scanning and walking motions of the robot while a second ground-based PC controlled the data acquisition functions for the eddy-current data. There was no communication between these PCs; data acquisition was initiated manually by the operator.

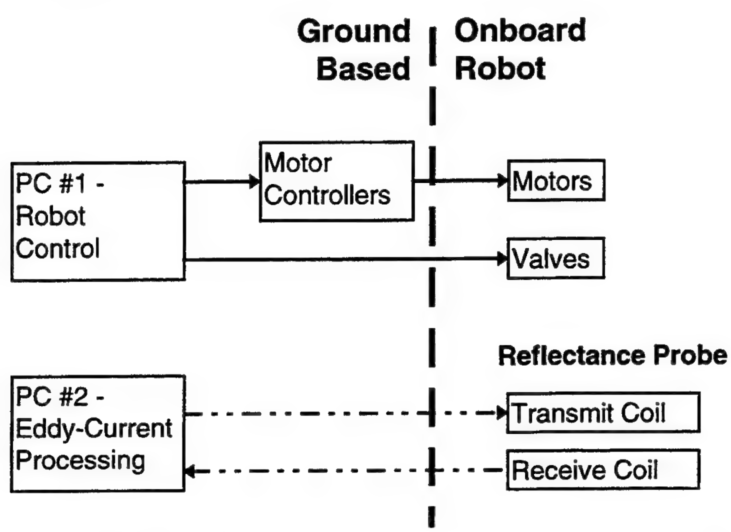

FIGURE 2. FIRST PHASE SYSTEM ARCHITECTURE

The robot control and operator interface software was monolithic; one software module was written for both the interface and control tasks. The eddy-current data acquisition task was controlled by commercial, stand-alone eddy-current system software.

The mechanical device was tested at orientations near horizontal and at modest slopes. Enhancements to allow the mechanism to traverse the entire fuselage were deferred until the next phase.

1.2 Overview of Current Inspection System

Since January 1993, the robot has become more capable in all aspects of operation. The mechanics have been upgraded to allow the robot to adhere and walk in all orientations on a

fuselage surface. The January 1993 version of the robot was limited to walking at orientations near horizontal or at modest slopes. Enhancements to allow the mechanics to traverse the entire circumference of the central fuselage region have been implemented.

The electronic and computer system architecture has been upgraded to more closely follow the originally envisioned architecture and is shown in Figure 3. A multiple computer architecture has been employed with communications between the individual computers using both point-to-point and LAN connections. A computer has been installed onboard the robot to control the low-level sequencing of mechanical operations and to monitor the status of the robot in real time.

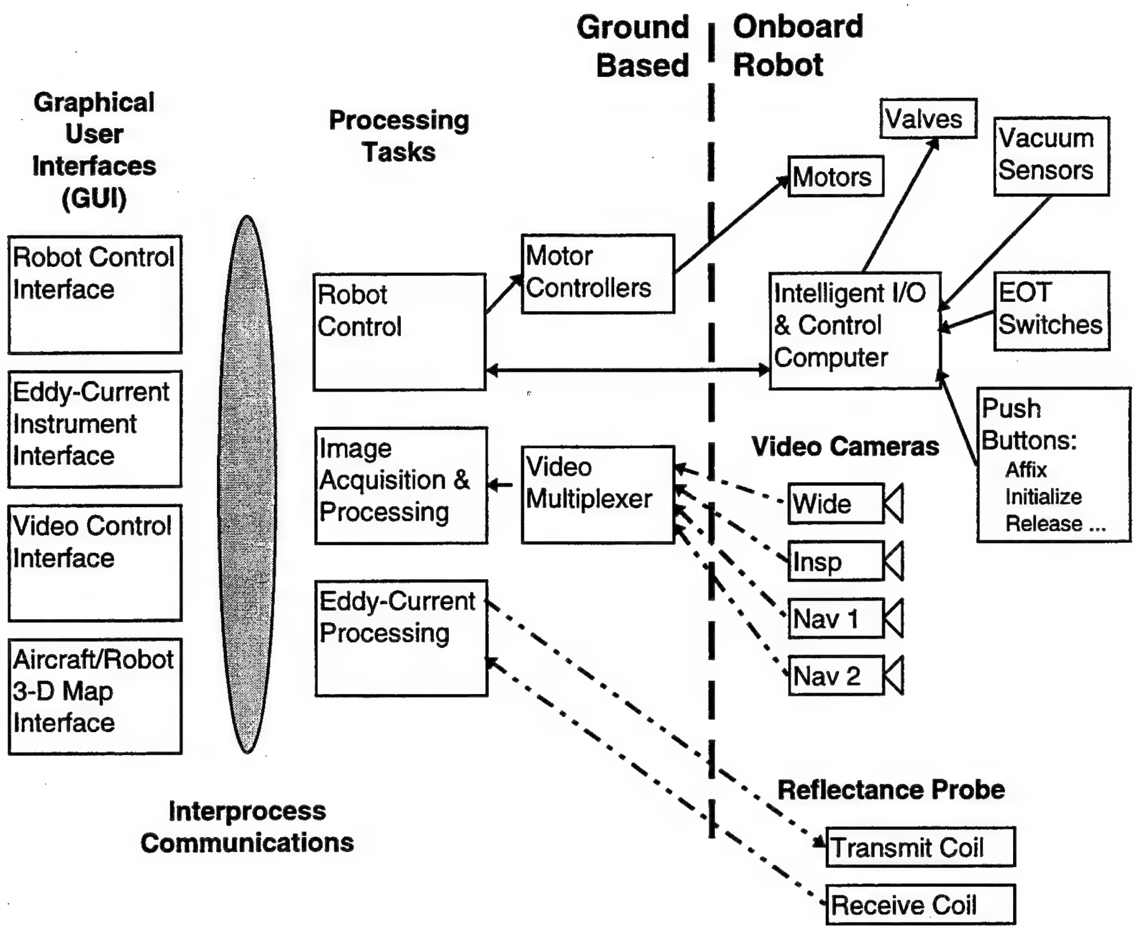

FIGURE 3. CURRENT SYSTEM ARCHITECTURE

Previously, the system's software was monolithic rather than modular. In the present version of the robot, the software has been designed to be modular, incorporating many cooperating processes. Multiple coordinated robot control and operator interface processes now exist. Intuitive, graphical, computer based controls for robot operation and sensor interpretation were added to simplify the use of the system.

The commercial eddy-current software was replaced with custom software which has been integrated with the other components of the system. Acquisition of eddy-current data can now be synchronized with the robot's movements by the robot's control process. Inspection data can be displayed to the operator or archived for later analysis.

Video cameras were added to the robot to enable the operator to navigate the robot over the surface of the fuselage and align the robot with the rivets to be inspected. Automatic algorithms to perform the alignment task were developed and tested under laboratory conditions; however, they have not yet been integrated with the system. The cameras also provide close-up images of the rivets being inspected and visual feedback of the robot's state to the operator.

The capability to overlay a 3-dimensional, wireframe model of the robot over selected aircraft models was added to the operator interface to provide navigational information.

Once these improvements had been made to the robotic inspection system, it was felt that additional testing of the system outside of the laboratory would be beneficial. The robot was deployed and demonstrated during the 1994 Air Transport Association (ATA) NDT Forum hosted by the FAA's Aging Aircraft NDI Validation Center operated by Sandia National Laboratories in Albuquerque, New Mexico.

The remainder of this report explains the current inspection system in greater detail.

2. MECHANICAL SUBSYSTEM

Since January 1993, the capabilities of the robot have been extended. As the system was tested, any limitations uncovered were noted to potentially be addressed in later phases of the project.

The cruciform robot was designed to adhere to surfaces in all orientations using suction cups, to walk across a curved surface, and to deploy sensors on a surface. The robot design is shown in Figure 4; pneumatic and electrical connections are not shown in this figure.

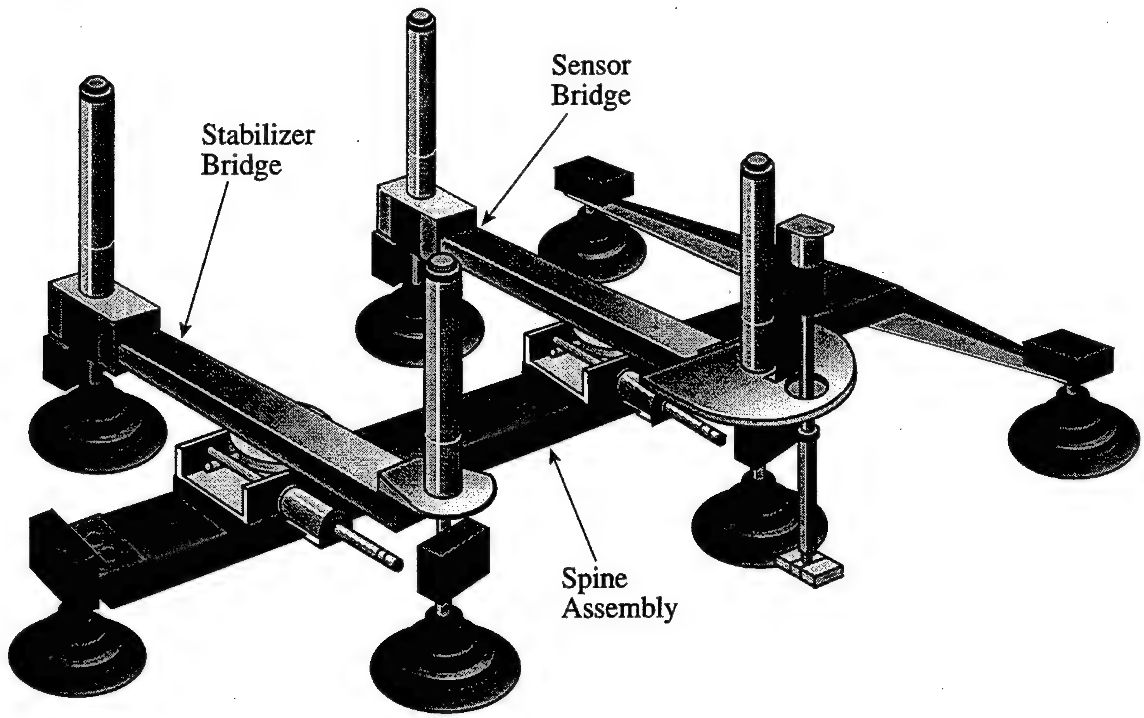

FIGURE 4. DRAWING OF THE CRUCIFORM ROBOT

The basic mechanical design of the robot is identical to that of the January 1993 robot which is outlined in [2]. The robot comprises a spine assembly and two bridges. The spine assembly is the main member upon which the bridges move. The sensor bridge possesses dual functionality. It is used to deploy the eddy-current sensor during scanning and is also used for support during walking. The stabilizer bridge is used only for support during walking, although later it might have an inspection role. The robot was made modular in this phase, meaning that each of the three subassemblies contains all of the components (e.g., valves, manifolds, etc.) necessary for its operations. A photograph of the current electro-mechanical assembly is shown in Figure 5.

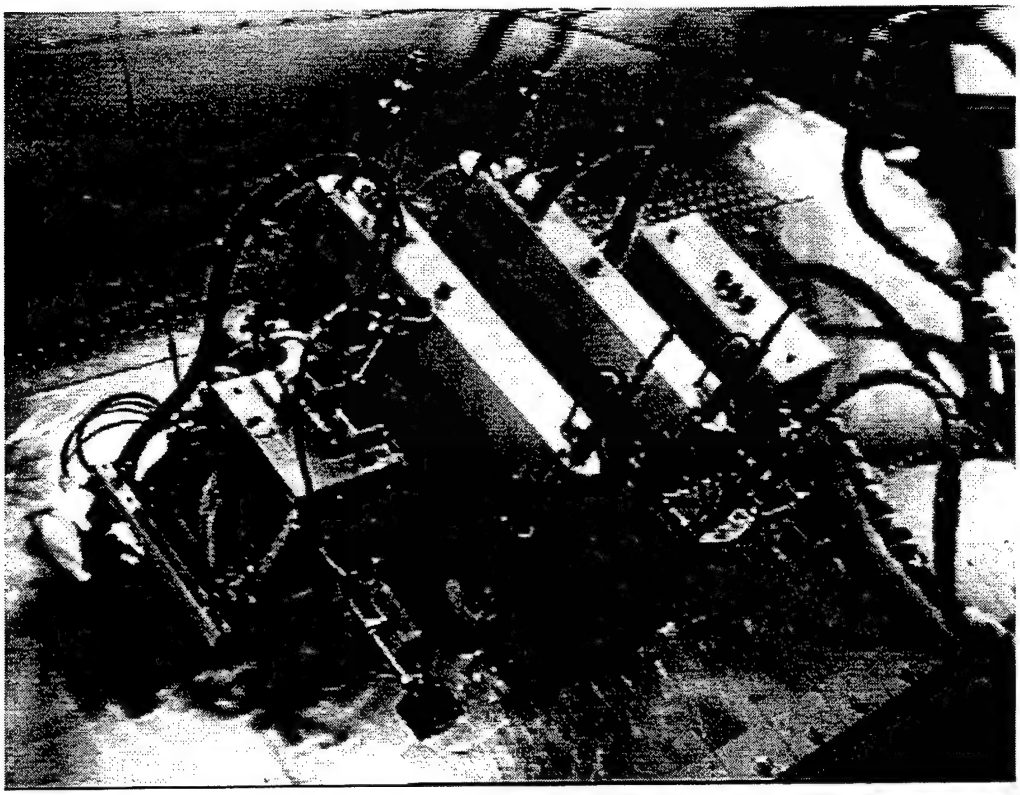

FIGURE 5. CURRENT ROBOT

2.1 Modular Design

Because the robot is a research prototype, it was decided to make the hardware modular to enable easy modifications for experimentation. The January 1993 version of the robot was not modular, and it was difficult to make changes or additions to the mechanical system without a major overhaul of the entire robot. In a modular robot, each of the bridges and the spine would be independent mechanically, pneumatically, and electrically. Thus, one could remove the sensor bridge from the robot, modify it, test it, and after it was working properly, reattach it to the robot. In fact, later in this section, the addition of a set of rails to the spine assembly will be described. The modular design of the robot enabled this change to be made with a minimum of disruption to the rest of the robot and with a minimum of downtime.

2.2 Leg Design

It was desired that the robot operate in a variety of orientations, simulating various positions on an aircraft fuselage. For the robot to be able to withstand the forces present in all orientations, its legs were stiffened. Two enhancements over the previous leg designs were implemented: the suction cup fittings were redesigned to reduce the tipping moment and to reduce the effect of the maximum shear force and a linear bearing assembly was added to withstand the maximum shear force. Figure 6 shows the present leg assembly.

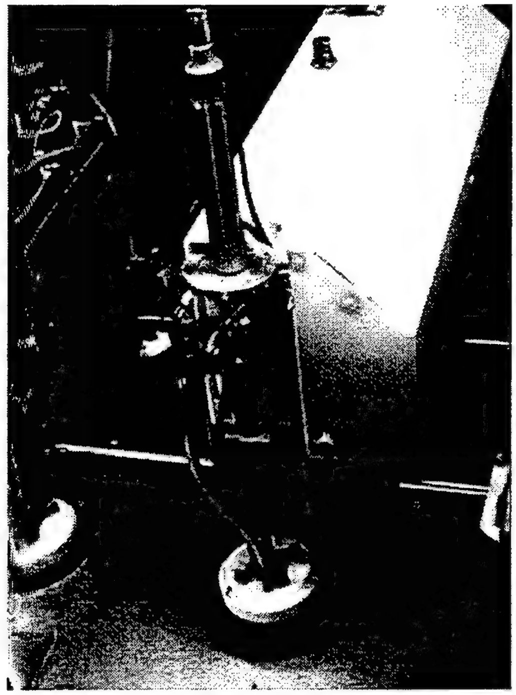

FIGURE 6. LEG ASSEMBLY

The suction cup from the previous phase was a commercially available, off-the-shelf item. It consisted of a 3-inch-diameter silicone suction cup, an aluminum suction cup fitting, and a ball and socket joint. There were two problems with this suction cup: the length of the tipping moment arm from the surface to the ball and socket joint created a large tipping moment, and according to the manufacturer, the ball and socket joint was not designed to withstand a shear stress. These problems had to be addressed to prevent a failure during the tests. The solution chosen was to design and fabricate a new suction cup fitting. The new fittings contained an integral ball and socket joint and were machined from P.E.T., a light-weight, easily machinable plastic material. The joint was designed to withstand the expected forces, and by lowering it into the suction cup fitting, the length of the tipping moment arm was reduced, thereby reducing the tipping moment.

The leg assembly from the previous phase was composed of the suction cup, suction cup fitting, the ball and socket joint discussed in the previous paragraph, and an air cylinder. Besides the problems with the suction cups, there was also a problem with attaching the air cylinder directly to the suction cup assembly. Exposing an air cylinder to shear loads over a prolonged period of time can break the seal around the rod, causing air leaks. To correct this problem, a linear pillow block bearing assembly was added to the leg configuration. The shaft of the bearing assembly was attached to the ball of the custom ball and socket joint previously described. The other end of the bearing shaft was connected to the cylinder rod via a linear coupler. Thus, in this design, all of the forces act upon the bearing assembly, and the cylinder is used only for motion. The air cylinder is not exposed to shear loads, thus, protecting the seal around the rod.

The legs on the spine assembly are fixed in place. A standard $\frac{1}{4}$-20 stainless steel stud is attached to the ball of the custom ball and socket joint. The studs are mounted

through holes at the ends of the head and tail beams and they are held in place using locking nuts.

2.3 Rails

When the robot was tested on surfaces approaching vertical, the linear motors that drive the bridges along the spine stalled. When the system was rebuilt to make the robot modular, weight was added to the bridges. The center of mass of each bridge was raised causing the torque about the linear motors to be too great. The torque about the motors caused the air gap between the motor and spine to become uneven, thus stalling the motor. To correct this problem, a pair of rails was added to the robot.

The rails are anchored in the head and tail beams of the robot and are parallel to the spine. Each bridge was equipped with two linear pillow block bearing assemblies which ride along the rails. Thus, the forces caused by the bridges' weight act only upon the rails and their associated linear bearings. This relieves the torque about the linear motors and the air gap remains uniform, thereby solving the problem of linear motor stalling.

2.4 Onboard Computer

As described in Section 3.1, an onboard computer was added to the robot. The printed circuit boards for the onboard computer are housed in a card cage on the head end of the robot as shown in Figure 7. A commercial card cage was modified and mounted on the robot.

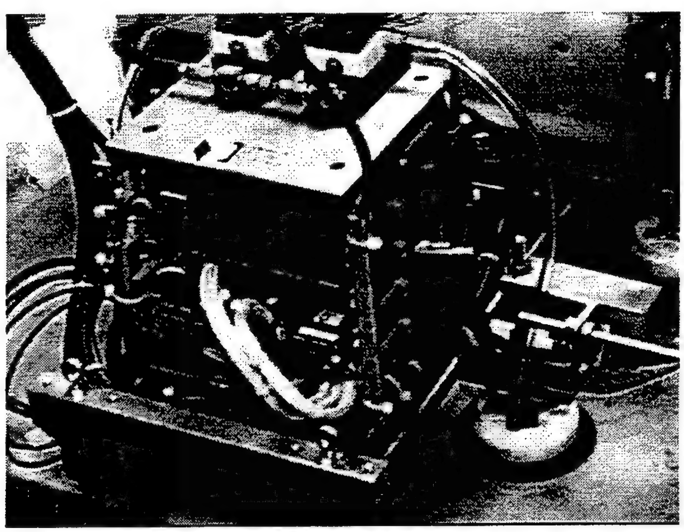

FIGURE 7. ONBOARD PROCESSOR

2.5 Tether

A tether was designed to keep the robot from falling to the ground if the robot's suction is lost. The basic principle behind the management of the tether is to pay out the tether as necessary while the robot moves along the aircraft panel; if the robot loses adhesion and starts to fall, the tether must be locked in position to keep the robot from falling. A standard safety device known as a retractor was used as the tether. The retractor

works much like an automobile's seat belt. With low acceleration, the cable is payed out as necessary; however, with a sudden acceleration the mechanism locks, preventing any more cable from being payed out. Custom bracketing was designed and fabricated to attach the tether to the head and tail beams of the robot. The tether is secured to a trolley that runs along a rail suspended above the area where the robot is deployed.

2.6 Marking System

The first concepts for a marking system were tested during this phase of work. The marking system was designed to physically mark the surface where abnormal sensor signals are encountered, allowing the inspector to locate and further inspect the marked areas at a later time. The marking system contains a spring-return cylinder and either a china marker or a self inking stamp. A three-way valve controls the operation of this feature, and the air pressure and flow to the cylinder are regulated to ensure an appropriate supply of air.

2.7 Feedback Switches

To give the robot a sense of self awareness, switches were added to provide feedback when actions were completed. Thus, when an action such as the extension of a leg occurs, an end-of-travel switch provides a signal to the control software to indicate that the action has been completed. Once the software has confirmation that an action has been completed, the next action in the sequence can be executed. If no signal is sent to the control software, the next action is not executed. This is in contrast to the previous phase where timing loops were used to allow enough time for the robot to complete an action, but no feedback was provided. Even if an action was not completed, the next action in the sequence was executed, and the operator was required to notice the problem and stop the robot. With the switches, the robot's gait has become much smoother.

Vacuum detection switches were also added to the robot during this phase. They are used to detect if the suction cups are holding to a surface. The vacuum switches have an adjustable threshold; if, for some reason, there were a vacuum leak around a suction cup and if the threshold were not reached, the suction cups already adhering to the surface would not be released. These switches are used to minimize the possibility that the robot will lose adhesion to the surface. The status of all switches is shown symbolically on the debug interface screen described in Section 3.4.3.1.

2.8 Air Consumption

The air consumption of the January 1993 prototype robot varied depending on several factors, for example, the number of suction cups activated at a given time. The maximum rate of air consumption for the robot was 7.2 standard cubic feet per minute (SCFM) of air. USAir inspectors had indicated that the robot should consume no more air than a standard pneumatic tool, about 5 - 10 SCFM of air. The January 1993 robot fell within this range; however, many standard air compressors that are used to run pneumatic tools do not produce 7.2 SCFM of air. The Carnegie Mellon team decided to reduce the robot's air consumption to a maximum of 6 SCFM to run the robot from most standard air compressors and to minimize pressure loss in the air line between the robot and the ground. The laboratory compressor produced 6.2 SCFM at 100 psi.

The air consuming parts of the sensor deployment unit and the pivot lock air bearings were eliminated. The pivot lock air bearings were replaced with a dry bearing. The airpot of the sensor deployment unit, which consumed 0.6 SCFM of air, was replaced by an air cylinder, which did not require a constant draw of air. On the spine assembly, to reduce the amount of torsion about the front suction cup and its ball and socket joint, a head beam, similar to the tail beam, and a second suction cup were added. Thus, the spine assembly increased from three to four suction cups. Accordingly, another ejector was added to provide suction for the extra suction cup.

The maximum rate of air consumption of the present prototype robot is 5.6 SCFM of air. During normal operation, only four suction cups are affixed to the surface. The normal requirement of air is 3.2 SCFM (four suction cups and the linear motor air bearings). When the robot is walking, during the transition from the spine legs being affixed to the surface to the bridge legs being affixed (or vice versa), all eight cups will be affixed to the surface for a brief moment. The moment when all eight cups are affixed to the surface plus the constant draw of the linear motors gives the maximum air consumption of 5.6 SCFM.

3. ELECTRONIC AND SOFTWARE SYSTEMS

3.1 Onboard Robot Electronic Systems

A block diagram of the electronic systems carried on board the robot is shown in Figure 8. A major improvement to the current robot is the addition of a dedicated computer carried on the robot. This processor manages all of the low level robot control, feedback, and sequencing in real time. A commercially available single board industrial computer is currently used for the onboard computer. This processor card provides integrated input/output capabilities over a -40° to 85°C operating range. Mechanical limit switches and vacuum switches provide TTL level signals to the CPU card for monitoring the robot's status. A reed relay expansion card provides the 12 VDC outputs used to drive the solenoid valves for operation of the pneumatic systems. Commands are received, and status information is sent via an RS-232 serial communication link with the ground based operator workstation. The eddy-current and video signals, as well as the motor drive signals are managed directly from the ground. A DC/DC power converter is used to generate the 5 VDC power required for the computer cards from the robot's normal 12 VDC supply.

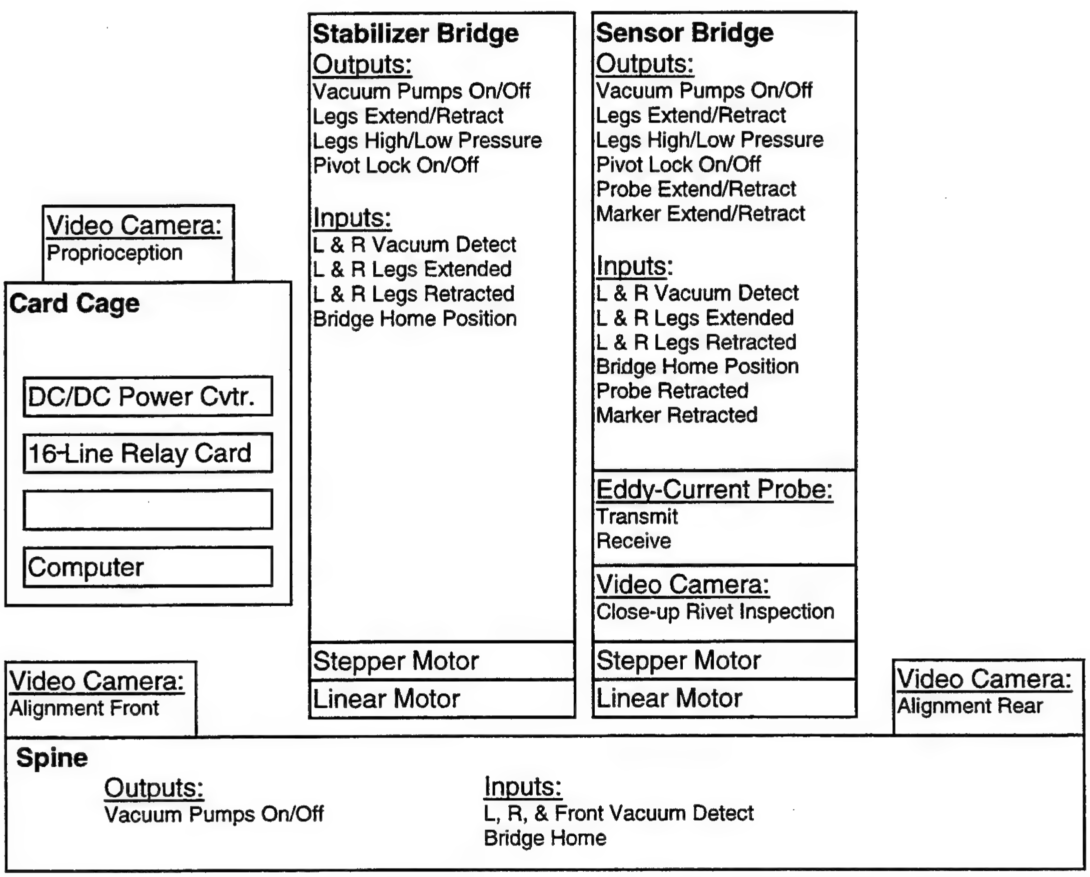

FIGURE 8. ONBOARD COMPUTER AND ROBOT ELECTRONICS

The onboard computer executes a multitasking program enabling complex sequences of actions to be simply controlled from the ground. A sample task called "SmplExtendV", short for "sample: extend robot legs with vacuum", would be used during a walking sequence when performing the transition from having the spine attached to the plane's surface to having the bridge legs attached and extended. The steps of this task break down to the operations:

1. set the leg cylinder pressure to low
2. extend the bridge legs
3. turn on the bridge vacuum pumps
4. wait until all four bridge suction cups have achieved vacuum
5. turn off the spine vacuum pumps
6. wait until all four spine suction cups have lost vacuum
7. complete extension by setting leg cylinder pressure to high

To perform this task the computer would execute the following instructions:

```
BB NewTask SmplExtendV
     WritePort SensHPBypass 0 EndInstruct
     WritePort StabHPBypass 0 EndInstruct
     WritePort SensExtend 1 EndInstruct
     WritePort StabExtend 1 EndInstruct
     WritePort SensVacuum 1 EndInstruct
     WritePort StabVacuum 1 EndInstruct
     SendMsg SmplExtendV:  Waiting for bridge vacuum make
EndInstruct
     ReadPortUntil SensVacDetR 0 EndInstruct
     ReadPortUntil SensVacDetL 0 EndInstruct
     ReadPortUntil StabVacDetR 0 EndInstruct
     ReadPortUntil StabVacDetL 0 EndInstruct
     WritePort SpineVacuum 0 EndInstruct
     SendMsg SmplExtendV:  Waiting for spine vacuum break
EndInstruct
     ReadPortUntil SpineVacDetR 1 EndInstruct
     ReadPortUntil SpineVacDetL 1 EndInstruct
     ReadPortUntil SpineVacDetFR 1 EndInstruct
     ReadPortUntil SpineVacDetFL 1 EndInstruct
     WritePort SensHPBypass 1 EndInstruct
     WritePort StabHPBypass 1 EndInstruct
     SendMsg SmplExtendV:  Done EndInstruct
     TaskDone EndInstruct
EE
```

Additional task capabilities include timed waits, other conditional and looping constructs, and the ability to stop or start other tasks.

3.2 Ground-Based Electronic Systems

The ground-based electronic equipment consists of three distinct components: the operator workstation computer, the video processing computer, and the satellite equipment enclosure.

3.2.1 Operator Workstation Computer

The operator workstation computer is the main control point for the robotic system. It provides the display and interface resources required by the operator to control and monitor the robot. These interfaces are described in further detail in Section 3.4.3. All high-level robot control and coordination are performed by this machine. Communication channels are provided to the motor controllers, the onboard computer, and the video processing computers. The eddy-current instrument is contained in and controlled by this machine. A photograph of the operator workstation is presented in Figure 9.

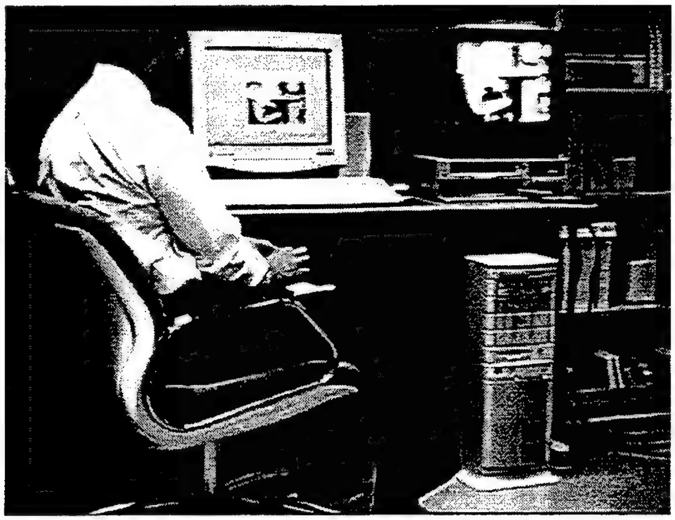

FIGURE 9. OPERATOR WORKSTATION & VIDEO MONITOR/RECORDER

3.2.2 Video Processing Computer

The video processing computer is used to perform all of the video switching and processing functions required by the system. It is configured as a separate machine because of the large amount of processing that will be required to perform the computer video analysis used for the automatic navigation and alignment capabilities which will be added to the robot in later phases of development. Thus, the processor resources used for image analysis are independent of the robot control, eddy-current data acquisition, and the user interface. A photograph of the video processing computer is presented in Figure 10.

3.2.3 Satellite Equipment Enclosure

The final ground-based unit is the satellite equipment enclosure. This is a small, mobile, 19-inch equipment rack used to house much of ancillary support equipment for the system such as power supplies, motor controllers, and the camera control units.

All electrical lines between the robot and the ground terminate at this enclosure. Communication and eddy-current signal lines are then routed to the operator workstation, while video lines go the video processor. A photograph of the satellite equipment enclosure is presented in Figure 11.

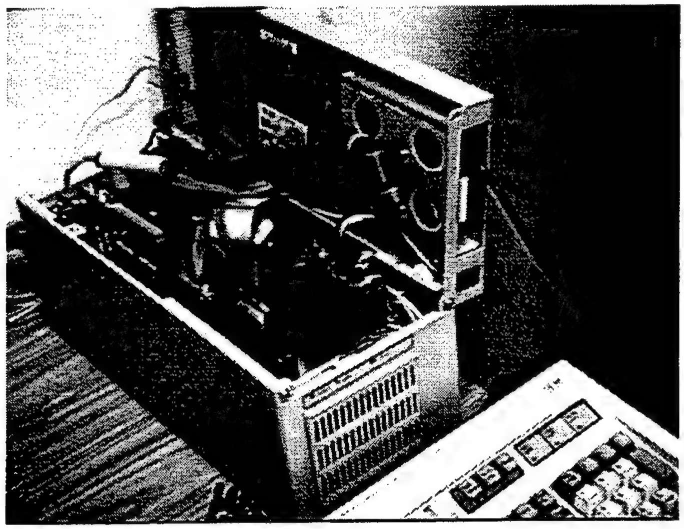

FIGURE 10. VIDEO PROCESSING COMPUTER

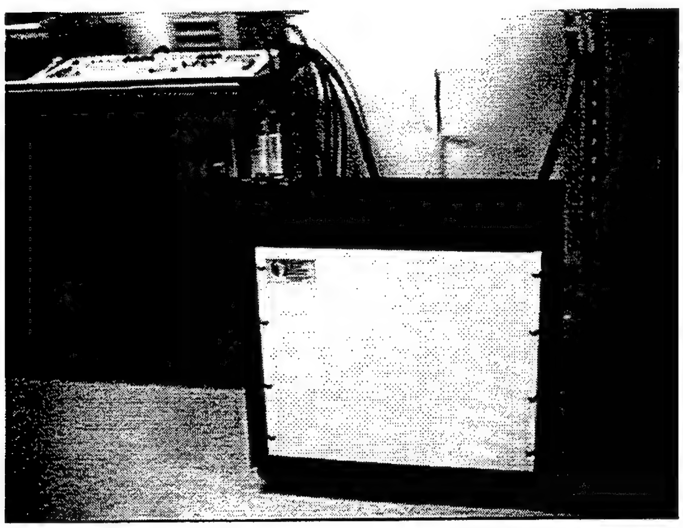

FIGURE 11. SATELLITE EQUIPMENT ENCLOSURE

3.3 Hardware Functional Descriptions

3.3.1 Communications Subsystem

The ground-based PC communicates with both the motor controllers and the onboard computer is over a set of RS-232 serial connections as shown schematically in Figure 12. While this serial communication configuration is sufficient for use in the lab, it is expected that a combination of RS-422 and optical isolation will be used in the hangar to support longer line lengths and to provide greater noise immunity. A four line serial interface is used to provide the additional communication lines from the PC. Software drivers enable these additional lines to be accessed in the same manner as standard PC COM ports. The 16450 UART ICs on the communication board were replaced with

16550 UARTs (with on chip character buffers) to provide more reliable high-speed serial communication links in the multitasking environment.

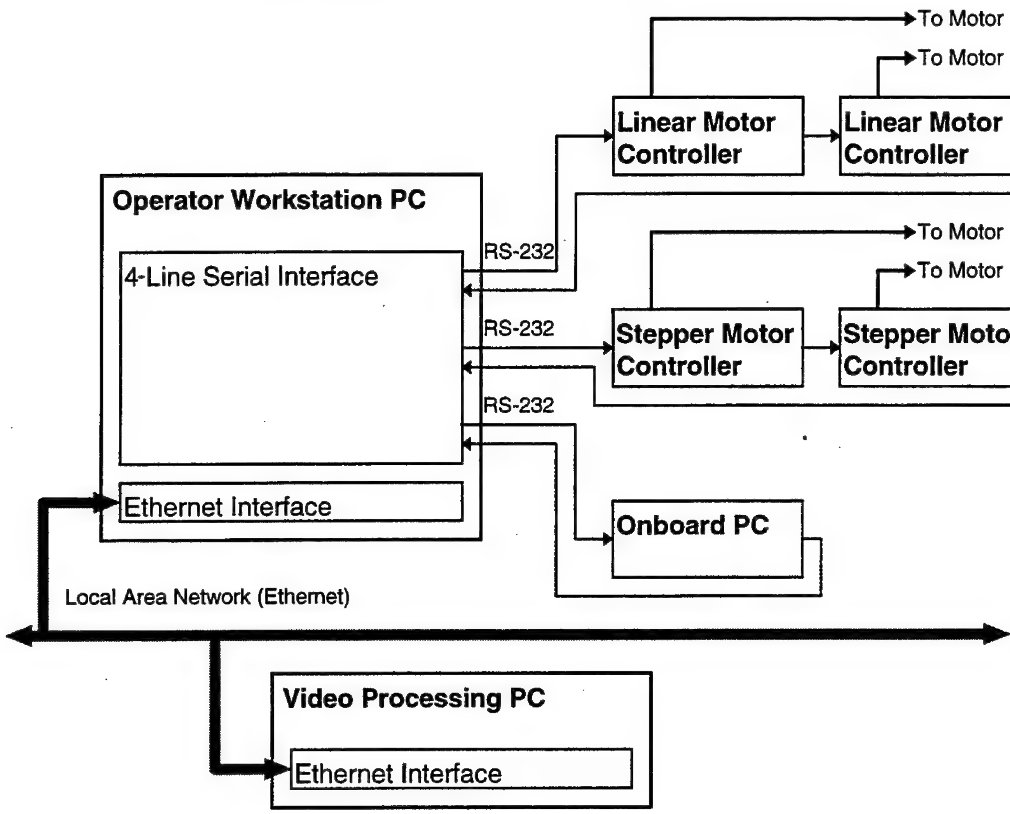

FIGURE 12. COMMUNICATIONS SUBSYSTEM

The stepper motor controllers drive the lead screw motors which are used to translate the bridges from side to side. The linear motor controllers drive the forcers which are used to move the bridges along the spine. Each of these motor controller systems is configured in a daisy chain, allowing multiple controllers to share a single communication line. Commands can be addressed to specific controllers, allowing independent motion control and status reporting for each bridge.

The operator workstation and video processor PCs are also connected to an Ethernet local area network. Communications between these two machines use standard TCP/IP protocols and enable high-speed command and image data exchange. This connection also provides access to resources on other computers such as disk storage, printers, and tape drives. Software development can be carried out on multiple computers and then easily transferred to the operator workstation as completed. This data path can also be used to provide access to the X-Windows user interfaces for control and monitoring of the robot through remote computers.

3.3.2 Eddy-Current Inspection Subsystem

Although the robot is capable of carrying any of a variety of small NDI sensors, it was decided to use a reflectance sliding eddy-current probe which is used in many real-world inspections. Deployment of this type of device has historically been carried out manually, with portable, self-contained instruments. These instruments generally do not

have the electronic interfaces required to incorporate them into larger systems. To embed an instrument into an automated data collection environment requires the ability to control the instrument and gather data through an electronic interface such as IEEE-488, RS-232, or a computer bus, e.g. ISA

An ISA bus based instrument manufactured by SE Systems, Inc., the smartEDDY™ 3100, was selected for the prototype robotic system. This instrument is capable of both reflectance and impedance measurements using dual inspection frequencies over the range from 1kHz to 10Mhz. It is installed in the operator workstation computer with 50-ohm coaxial cable connections to the Nortec SPO-1958/913918 sliding probe installed on the robot sensor bridge.

3.3.3 Video Subsystem

Video imagery provides useful information in both direct support of the eddy-current inspection as well as improving the teleoperation capability of the robot as a whole. A total of four video cameras are currently installed on the robot to support navigation and alignment, close-up visual rivet inspection, monitoring of the robot, and large area visual inspection. A block diagram of the video subsystem is provided in Figure 13.

Two Chinon CX-060 miniature black and white video cameras are used for navigation and alignment of the probe with respect to the rivets on the fuselage. One camera is placed at each end of the robot's spine assembly looking down at the aircraft's surface. To provide additional operational feedback to the operator, two Elmo MN401E 1/2-inch CCD, (768H x 494V pixels), color cameras were also placed on the robot. The first is the "proprioception camera" which is mounted at the front end of the robot on top of the computer card cage. This camera has a wide field of view and is aimed back over the robot so that the operator may view the robot and its immediate surroundings. The second color camera is mounted on the sensor platform and is aimed at the eddy-current probe. This camera provides a detailed visual view of the rivets that are being inspected. The color cameras each require an auxiliary control unit, located in the satellite equipment enclosure, and a multiconductor control cable.

The selection of the currently active video input from the available video sources is done by the computer using the video multiplexer which has twelve video inputs and seven video outputs. The video signal is digitized by the EPIX 4MEG VIDEO™ Model 12 video digitizer/processor. This card has 4Mb of video memory, a 14.3 MHz pixel clock, and a dedicated TMS320C25 12MIP digital signal processing chip. It is capable of driving an RGB video monitor with either live or processed video imagery. Both of these cards are installed in the video processing PC.

A video monitor is normally used to display the video data to the operator. However, the capability exists to display the video data in a subwindow within the computer monitor. A video recorder is provided to archive the video data from the cameras as well as to feedback previously recorded data into the system for the testing and validation of image analysis algorithms.

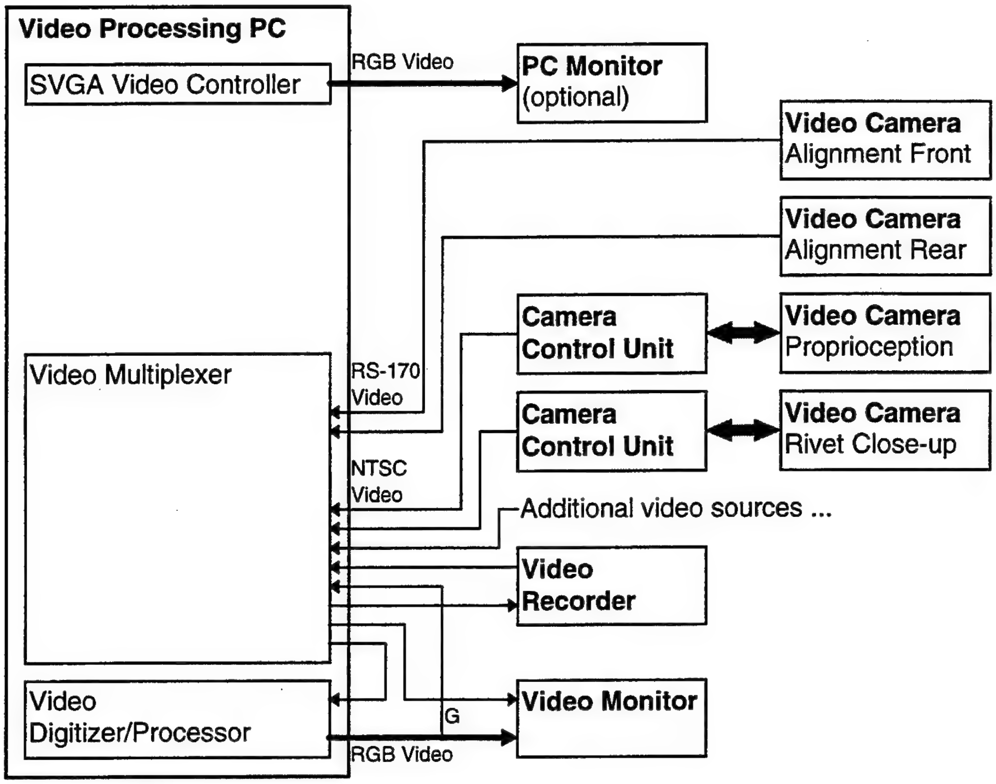

FIGURE 13. VIDEO SUBSYSTEM

3.4 Software Functional Descriptions

This section covers the processing tasks and graphical user interfaces shown in Figure 3.

3.4.1 Interprocess Communications

Coordination of the various software processes requires them to exchange information while executing. The interprocess communications entity shown in Figure 3 is in control of all communications between any of the processing tasks or between the graphical user interfaces and the processing tasks. It currently routes text or binary messages between the software entities executing on the operator workstation. A future development goal is to extend the capability of the interprocess communication software to include other hosts on the LAN through the use of the TCP/IP socket level programming model.

3.4.2 Processing Tasks

3.4.2.1 Robot Control

The robot control process controls all higher level robot functionality. It currently supports the following operations:

- Walk (forward, back, left, right)

- Scan (forward, back)
- Home (calibrates motor position by sending bridges to a known location)

The robot control process provides the command interface to the motor controllers and the onboard PC and maintains a copy of the current robot status.

3.4.2.2 Eddy Current

While a self-contained eddy-current inspection software package was included with the SE Systems, Inc. instrument, it was structured as a dedicated application. It could not exchange information with other parts of the control program, and it required the entire capacity of the machine. To integrate the eddy-current instrument with the robotic system, a custom software interface was written. The eddy-current process is used to set the parameters of the instrument such as inspection mode, signal level, signal frequency, and sampling rate.

The eddy-current process also performs the actual acquisition and buffering of the inspection data. The current system can support data sampling rates of approximately 1 kHz. Display or further processing of the data is left to the eddy-current user interface.

3.4.2.3 Video Processing

The video processing application runs as a TCP/IP network server on the video processing PC. It sets up the video digitizer and multiplexer hardware and then listens on the local area network for commands from the operator workstation PC. Video data may be acquired and displayed from multiple sources, saved to or restored from disk, and overlaid with an alignment cursor.

Overlaying the video from the front and rear alignment cameras with a calibrated cursor enables the operator to manually align the robot with the rivet rows. This function enables manual operation of the robot in the short term while the automatic alignment algorithms, described in Section 3.4.4.2, are developed and integrated into the system.

3.4.3 User Interfaces

Graphical user interfaces were developed to simplify the use of the system and the display of inspection data. Controls are provided using a combination of pull-down menus, push buttons, text fields, and command lines. Feedback from these actions are rapidly provided through visual indication of the robot's status, graphs representing eddy-current data, and wireframe models of the robot and the aircraft being inspected.

The X-Windows interface was chosen for implementation of the robot system due to its portability to multiple types of computers and operating systems. The interface was implemented using a client/server model and is usable over a network. This allows multiple computers to transparently share inspection subtasks and results. The use of X-Windows also allows multiple interfaces to be simultaneously displayed in separate windows on a single computer monitor. Samples of the user interfaces are presented in Figures 14 through 22.

3.4.3.1 Robot Control

Control of the robot and feedback of its status is provided through the control/debug, router, and message interfaces.

The control/debug interface, Figure 14, provides interaction with the robot graphically, through a schematic representation of the physical robot hardware. The spine and both bridges are presented. Individual control points are accessible via on/off or arrow push buttons. Selecting these buttons with the mouse sends commands to the onboard computer to turn pneumatic valves on or off, or to move the motors. Status information obtained from the robot is indicated through color changes in the display:

- control points, (On=White, Off=Gray)
- limit switches, (On=Yellow, Off=Gray)
- suction cups, (Vacuum=Green, Ambient pressure=Red)

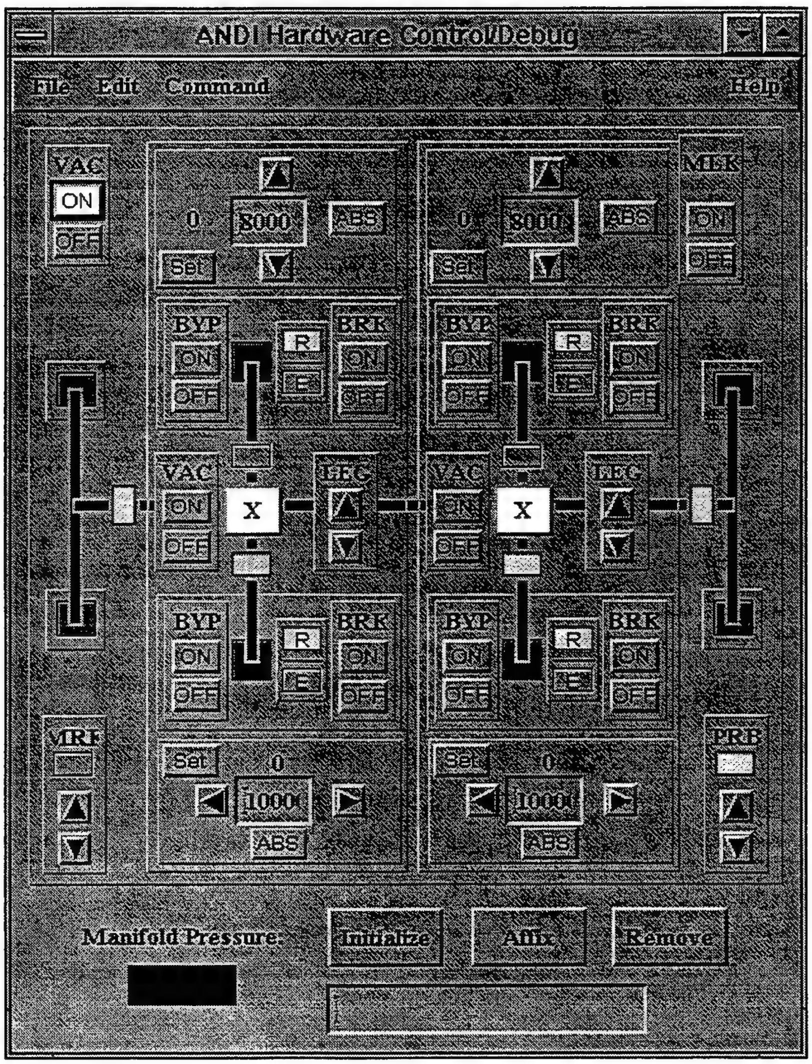

FIGURE 14. ROBOT CONTROL INTERFACE

The ANDI command interface, shown in Figure 15, sends textual commands to any of the cooperating interfaces or processes through the router process. This provides

support for both system debugging as well as more complicated motion sequences run from the control process. These moves include walking, scanning, and homing the robot's motors.

For system debugging purposes, low-level messages from the onboard computer are displayed in the communication screen, Figure 16. The current status of each of the robot's inputs and output are divided into groups of eight bits, forming data bytes which are displayed using hexadecimal notation. There are currently five input and five output bytes used to reflect the robot's status. Output transitions, text messages generated by tasks, and text responses to debugging commands are also displayed here.

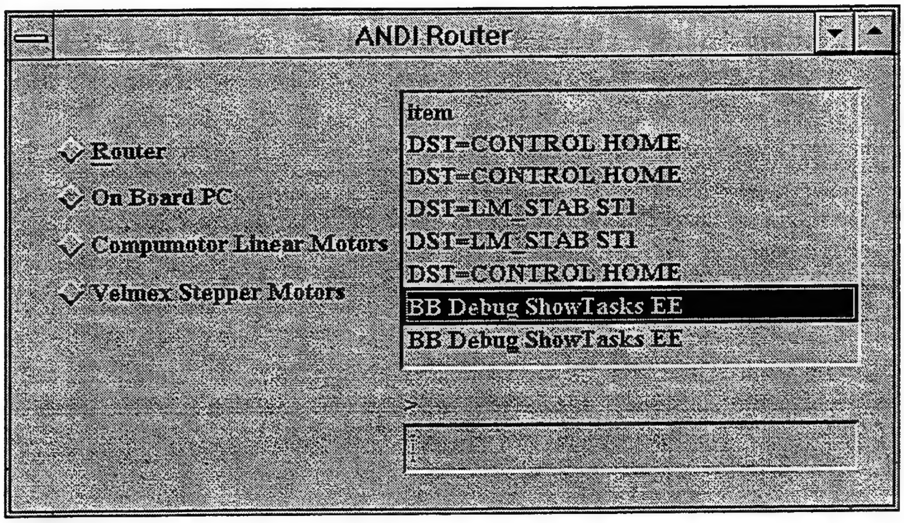

FIGURE 15. COMMAND INTERFACE

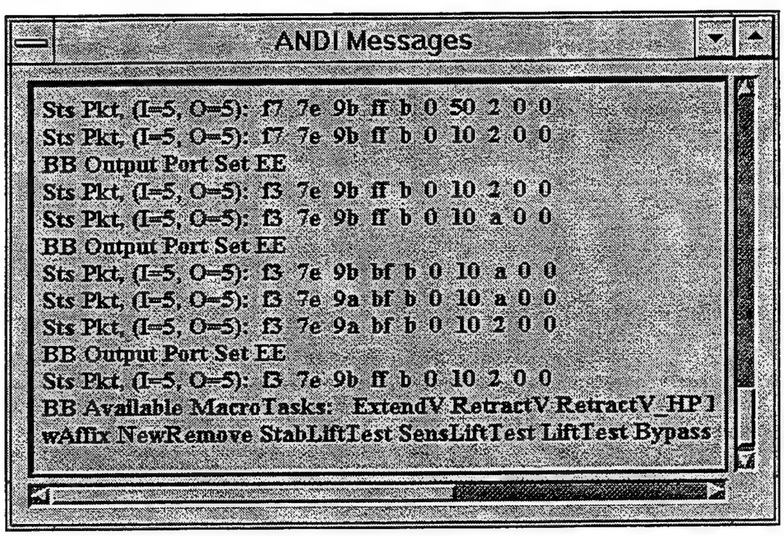

FIGURE 16. COMMUNICATION DISPLAY

3.4.3.2 Eddy-Current Instrument Control

The eddy-current control interface is used to control the inspection parameters of the eddy-current instrument, as well as to display the acquired data.

The inspection parameters that can be set in the eddy-current control screen in Figure 17 include:

- A and B channel oscillator frequencies and levels
- reflectance or impedance inspection mode via the signal selection relays
- data sampling rate

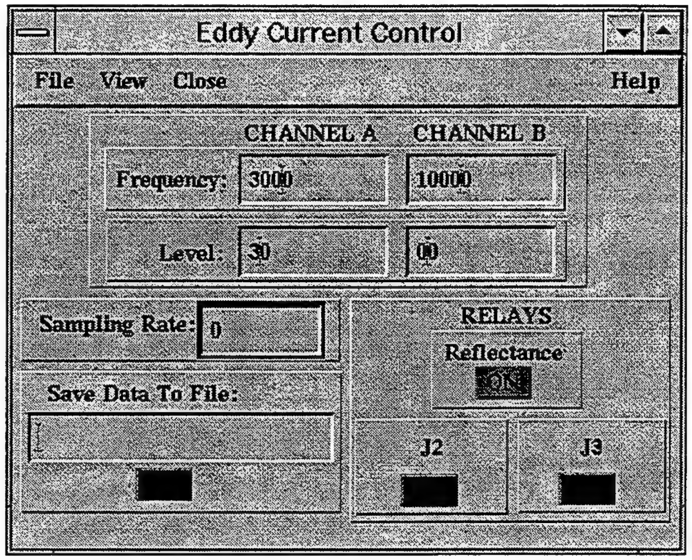

FIGURE 17. EDDY-CURRENT INSTRUMENT INTERFACE

Acquired data may be displayed to the operator or also archived to a file for later analysis. The data can be presented in both textual, shown in Figure 18, and graphical forms. The graphical displays can plot the data as In-phase vs. Quadrature signals, Figure 19, or as separate In-phase vs. Time and Quadrature vs. Time plots, Figure 20. Each frequency channel is displayed in a different color and the operator has the ability to zoom in on selected sections of the plots to view the data in greater detail.

There is currently no automatic flaw detection capability in the eddy-current software. Simple, threshold-based flaw detection algorithms may be incorporated to more fully demonstrate the autonomous operation of the inspection system.

3.4.3.3 Video Control

The video control interface is used by the operator to manually adjust the robot alignment prior to eddy-current inspection. It consists of both text and graphically based commands and is shown in Figure 21. Text-based scripts are used to send commands to the video processing PC to select the active video input and to overlay the video cursor for the front and rear alignment cameras.

The graphical user interface is used to set the robot in the alignment mode with legs extended and pivot locks off. The operator can then rotate and jog the robot to bring the eddy-current sensor into the correct position for scanning by depressing the mouse button and dragging the mouse while the cursor is in the black rectangular region of the display. Once properly aligned, the robot is returned to scanning mode with legs retracted and pivot locks on.

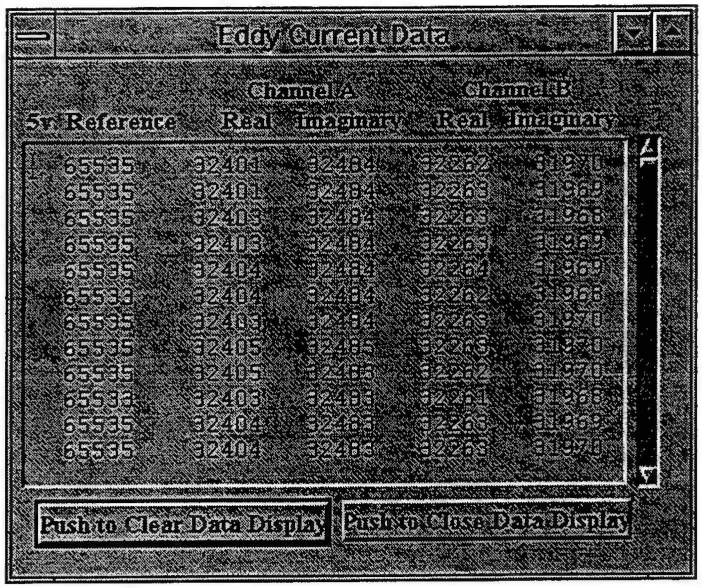

FIGURE 18. EDDY-CURRENT TEXTUAL DATA DISPLAY

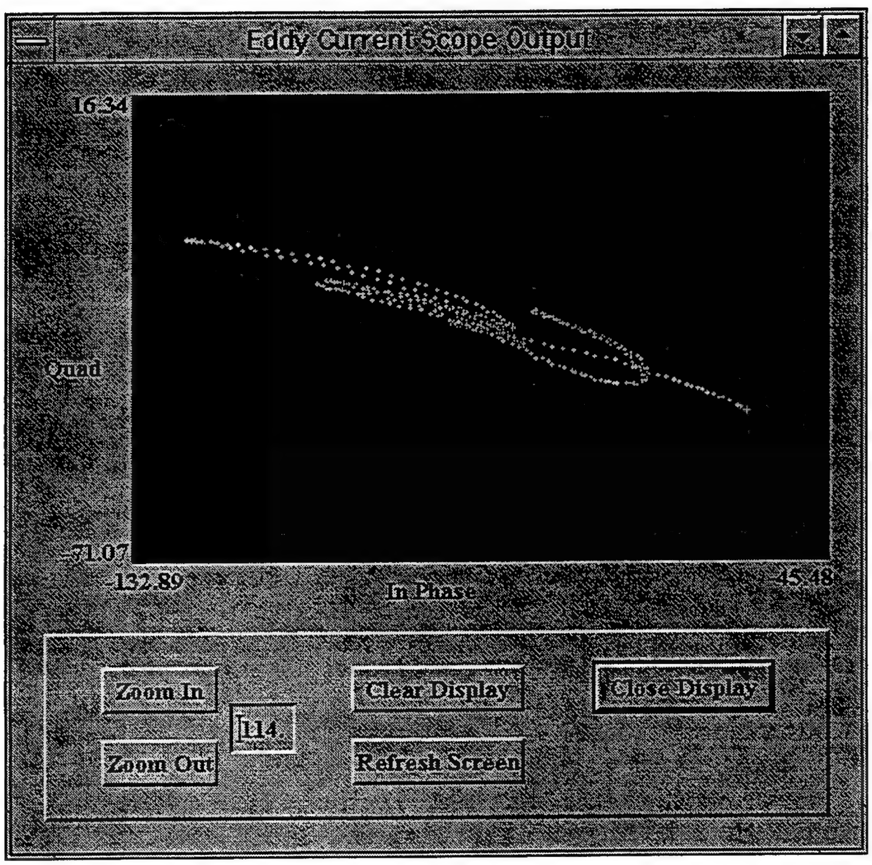

FIGURE 19. EDDY-CURRENT IMPEDANCE PLANE DISPLAY

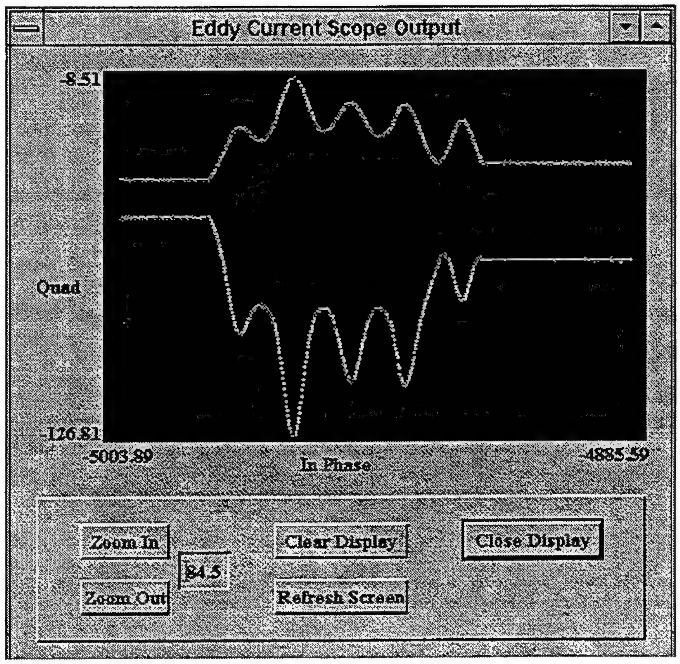

FIGURE 20. EDDY-CURRENT IN-PHASE/QUADRATURE VS. TIME DISPLAY

3.4.3.4 Aircraft/Robot 3-D Map

A prototype graphical display of the robot's inspection path was created using a three-dimensional wire-frame representation of the surface of the airframe under inspection. While CAD data obtained directly from the aircraft manufacturer or the airlines would be preferred for use as the basis for aircraft maps, it is typically not available for the older generation aircraft now being inspected. An alternative is the use of models of various aircraft which are available from computer animation companies. While these models are optimized for their visual representation and do not generally include structural information, they do provide a sufficient framework to provide navigation information at the resolution required by the robotic system. The frame and stringer or longeron intersections serve as navigation points whose approximate location can be obtained from service documentation and measurements from the aircraft. These intersection points define the lines where rivets are found and can be manually fit to the aircraft model using computer aided drafting tools. Individual rivets are not modeled. In addition to the ability to model aircraft, information concerning test fixtures, such as the Foster Miller laboratory skin panel, are easily input. A sample display of the lines connecting the frame and stringer intersections on the Foster Miller test panel used in the laboratory is provided in Figure 22.

The operator currently has the ability to import various map data files into the viewport and modify the point of view. Rivet lines are indicated in a contrasting color. Eventually, the operator will be able to define, via an input device such as a mouse, the robot path by selecting appropriate lines of rivets for inspection. Areas that are selected for inspection or have been inspected or where anomalies have been found may all be indicated through the color used to display the segment. It is also possible to overlay an image of the robot on this display to monitor the position of the robot on the aircraft being inspected.

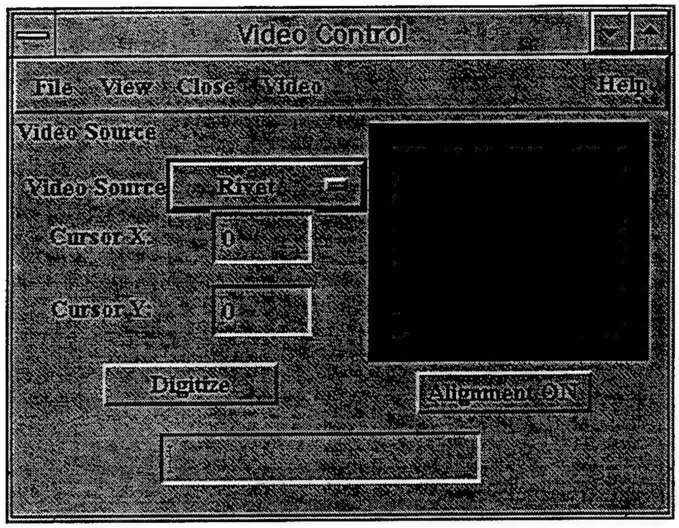

FIGURE 21. VIDEO CONTROL INTERFACE

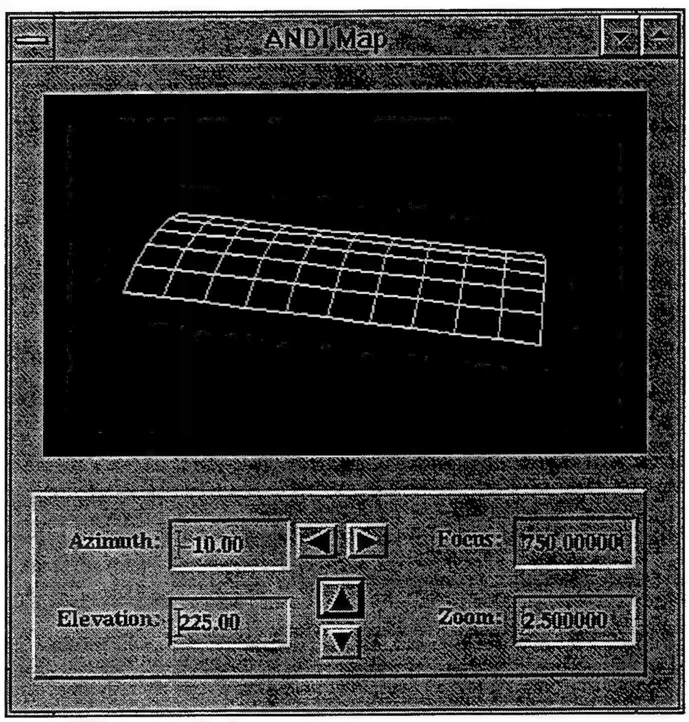

FIGURE 22. AIRCRAFT MAP DISPLAY (FOSTER MILLER PANEL)

3.4.4 Miscellaneous

There are two additional software efforts, detailed in the following sections, that are supporting the robotic system's long term development. Techniques developed through this research will be incorporated into the robotic system as appropriate.

3.4.4.1 Robot Animation

The U.S. Bureau of Mines has developed a three-dimensional animation and rendering of the robot and aircraft surface. This tool, which runs on a Silicon Graphics

workstation, enables the visualization of the robot's motion and its interaction with the surface being inspected. The animation of the robot can be controlled using either predefined scripts of motion commands or via the X-Windows robot control interface described in Section 3.4.3.1.

3.4.4.2 Video Rivet Location Algorithms

To allow the robot to align the eddy current probe to the rivets undergoing inspection as well as to navigate autonomously over the aircraft's surface requires algorithms to detect the presence and measure the location of rivets in the video imagery from the navigation cameras, and also to abstract from the detected isolated rivets the imaginary "lines of rivets" that form the natural reference grid for navigation and the natural scanning paths for the eddy current inspection probe. Algorithms to do this rivet detection and rivet line abstraction were developed at the CMU Robotics Institute. A demonstration of rivet image-based alignment with, and navigation along, a grid of rivet holes in a sample of DC-9 belly skin was performed and videotaped to verify the ability of the algorithms to function correctly in a closed loop control system. The rivet finding and rivet line abstraction algorithms will be transferred into ANDI's video processing system during the next phase of the project. The key features of the approach and demonstration are summarized in the following paragraphs and detailed in a conference paper[3].

If the rivets that hold an aircraft's skin to its frame all looked the same, then it would be easy to construct a dedicated algorithm that would reliably find and mark all the rivets in an image. However there are many types of fasteners in use on new aircraft, many more types in use on in-service aircraft, and even identical fasteners on the same aircraft take on different appearances depending on the details of their installation, location, weathering, buffing, coating, etc. To accommodate this variation range, we adopted an open ended approach using a neural network architecture than learns from visual examples presented to it and classified by a human "trainer" as containing or not containing rivets. The visual examples are small square "windows" on the full image; a window's side is about twice the diameter of the largest rivet head that will be encountered. Thus the window may contain all or part or none of a rivet head, but it will rarely contain more than one.

In operation, the trained neural network generates a numerical output, that we call "rivetness", that represents its estimate of the probability that the window it is being shown contains a rivet. The window is scanned over an image resulting in a "rivetness" map that is bright in areas where rivets are probable, dark in areas where they are improbable, and gray in ambiguous areas. A sample of the "rivetness" image is provided in Figure 23. Via several subsequent conventional image processing steps the "rivetness" image is converted to a black-and-white (binary) image in which rivets are white, non-rivets are black. The binary image obtained from Figure 23 is shown in Figure 24. The binarization process completes the rivet finding step.

Next, it is necessary for the computer to abstract isolated rivets into rivet lines and a rivet line grid; this kind of abstraction, which is the natural thing for the human brain to do when it is presented with isolated dots that happen to fall on lines and rectilinear grids, is a potentially difficult task for a computer. It is a simple and very common procedure to fit a line to a set of data points in some coordinate system, e.g., by the least squares method, but exactly where this line falls can be very strongly influenced by a small number of points that are far from the main distribution; that is, these methods

are inappropriately sensitive to outliers. Any image containing a line of rivets will probably also contain a few extraneous rivets that would be effortlessly rejected as irrelevant by any human but that would not be recognized as irrelevant by conventional line fitting algorithms. Fortunately, modern statisticians have recognized this problem, and in response they have developed robust line fitting methods that do an excellent job of focusing on the main stream and ignoring the outliers. These algorithms have been extremely successful in identifying rivet lines. The line in Figure 24 is the output of the robust line fitting algorithm.

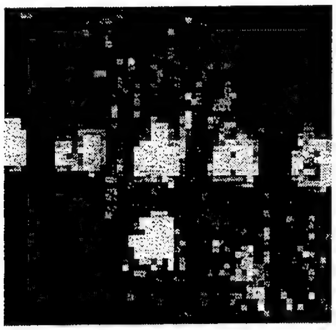

FIGURE 23. RIVETNESS IMAGE

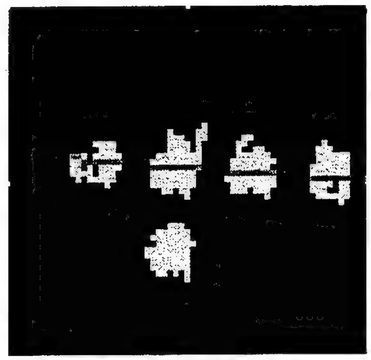

FIGURE 24. BINARY IMAGE WITH LINE

An existing Robotics Institute laboratory robot, that was built as a development platform for enhanced visual inspection sensors, was used to test the rivet detection and line fitting algorithms. The "test inspection platform" (TIP) robot is capable of pure rotation (with negligible forward/backward or left/right motion), so it could follow the requested path precisely despite the path's right angle corners. It was guided around a rectangular path under the closed loop control of the algorithms. To provide a rapid demonstration-of-principle, we assembled a multicomputer pipeline in which the tasks of image collection, image transmission, rivet detection and rivet line abstraction, robot control strategy generation, robot control command generation, and robot control command execution were done on several different workstations, in several different locations, communicating over the campus Ethernet LAN. Although the decision making process was slow, primarily because of the need to move large image files over the Ethernet, the navigation sequence was executed without error, the path following accuracy was excellent, and the TIP robot always discovered and corrected random orientation errors that the top-level program introduced to challenge the lower-level programs.

4. SYSTEM TESTING AND FIELD DEMONSTRATION

A panel fixture to support a simulated aircraft panel was designed and fabricated for testing the robot in the laboratory. This fixture allows the panel to be rotated 360° and locked into any desired position for testing. The panel fixture, shown in Figure 25, allows the robot to be tested in all orientations, simulating the top, bottom, and sides of an aircraft. A trolley runs above the panel for tethering the robot. The robot can be seen sitting on a cabinet in the foreground of Figure 25.

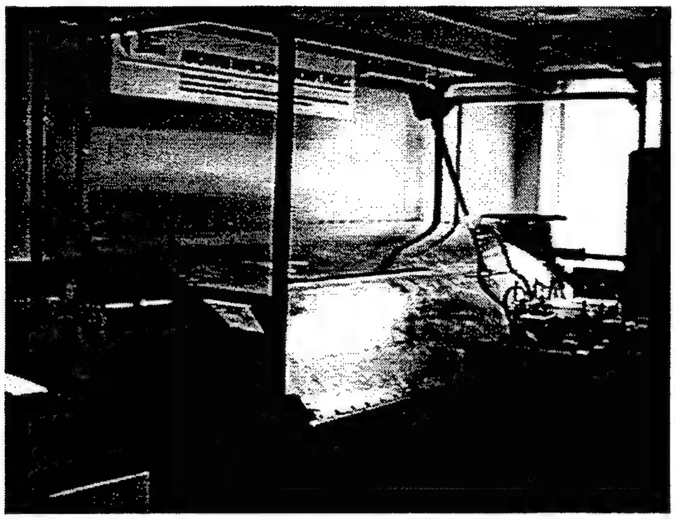

FIGURE 25. LABORATORY TEST PANEL FIXTURE

ANDI was demonstrated at the Air Transport Association's Nondestructive Testing Forum on November 2, 1994, at the FAA Aging Aircraft NDI Validation Center (AANC) in Albuquerque, NM. Prior to this demonstration, extensive laboratory and hangar tests were conducted. A picture of the robot walking on the DC-9 nose section is shown in Figure 26.

This remainder of this section outlines the issues uncovered during the period of laboratory testing and preparation for the field demonstration.

4.1 Linear Motors

Several problems associated with the linear motors were found during system testing. The linear motors tended to stall following 1/2 to 3/4 hours of use. The motors generate heat when they are used, and there is no efficient way to dissipate the heat. Because the platen (spine) was machined into a U-channel to save weight, there is very little material for heat conduction. This lack of material most likely causes a thermal expansion of the platen, and over time, the platen expands enough to cause the motors to stall.

Severe wear was also noted on the linear motor platen; this may have two causes. First, the thermal expansion of the platen may cause wear on the platen before the motors stall. Also, because the platen was machined into a U-channel, it may not be perfectly flat, causing the motors to rub against the surface of the platen, creating wear. The Stabilizer Bridge did not move freely even when the system was cold, indicating that the spine may not be uniformly flat.

Finally, there was a loss of motor position calibration after either of the bridges ran into a hard stop or after the bridges ran into each other. If this happened, the motors had to be sent back to their home positions for proper initialization.

Enough problems with the linear motors were uncovered that it might be best to explore other options for creating linear motion along the spine.

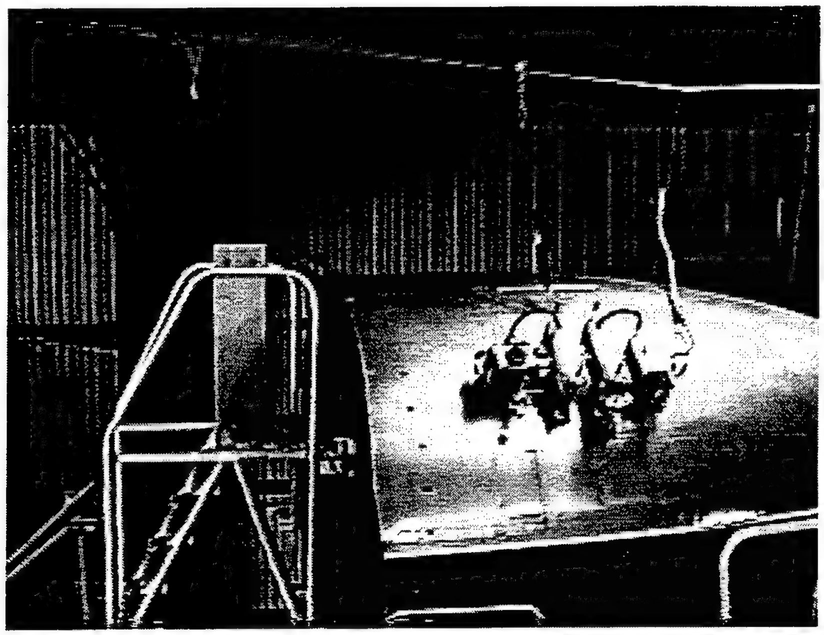

FIGURE 26. ROBOT ON DC-9 NOSE SECTION

4.2 Lead Screw Assemblies

The lead screw assemblies that provide linear translation in the direction perpendicular to the spine were slow, on the order of 10 inches per minute. When the motors were run at higher speeds, they did not provide enough torque for motion. The installation of higher torque motors for the same assemblies provided only marginally greater torque at higher speeds, and speed was not measurably increased. This issue needs further investigation.

4.3 Umbilical/Tether Management

The problems inherent with managing both a thick umbilical cable and a tether are operational issues that must be solved before surface-crawling robots can effectively be used in a commercial aircraft inspection facility. Although these issues are beyond the scope of this project, it was apparent from the field demonstration that tether and umbilical management are critical.

The umbilical is the line that extends from the control area to the robot. Presently, the umbilical comprises: three 1/4-inch pneumatic lines, two eddy-current cables, four video cables, four motor control cables, a power cable, and a computer communications cable. The diameter of this bundle is about 1-1/4-inches.

During the demonstration, the robot walked over the crown of the nose section of a McDonnell Douglas DC-9 (the section that stretches from the nose of the aircraft to just past the second passenger window). For this, the length of the umbilical cable was 50 feet; it was very difficult

to manage a cable of that thickness and length. To inspect the entire fuselage of a DC-9 or other aircraft, the robot would require a much longer cable. If the robot were to inspect a wide-body aircraft, several hundred feet of umbilical cable would be required. If robotics is to be practical in a commercial hangar environment, the umbilical must be either made more manageable or perhaps eliminated altogether.

The tether for the demonstration ran along a safety line suspended above the DC-9; however, the tether did not move freely enough to gracefully move in concert with the robot. There were times when the tether became entangled with the bridges, thus interfering with the robot's motion. In the future, coordinated motion between the tether and the robot may be necessary. An active tether whose motion would be in sync with the robot is an area of potential research for the future.

4.4 Navigation

During the field trials, it was noted that navigation around seams was complicated by the spacing and size of the suction cups and the 3-1/2-inch sideways step size of the bridges. There are several potential solutions to this problem. First, clusters of suction cups could be added to each leg; this would have the disadvantage of increasing the amount of air used by the system. A second potential solution is to adjust the dimensions of the bridges to make navigating around seams easier.

4.5 Walking Motion

The walking motion of the robot created some operational problems. On inverted, angled surfaces, the extend and retract motion, in which the spine is raised from and lowered to the surface, was unreliable. This was primarily due to a combination of the weight of the robot and the sizes of the pneumatic lifting cylinders. Also, the extend and retract motion severely jars the mechanical system, loosening and breaking electrical contacts and shifting camera views. A third problem with the walking motion is that the variation in the robot's position between the extended and retracted states makes alignment difficult. Alignment is performed in the extended state while scanning occurs in the retracted state. One apparent solution for these problems is to replace the legs on the spine assembly with legs that can extend and retract. During walking, the spine would stay at a uniform height while the individual legs would be raised and lowered.

4.6 Surface Damage

During field testing, it was noted that the suction cups left scuff marks on the aluminum skin; the situation was much worse on the Foster Miller panel than on the DC-9 fuselage surface. This problem may be connected with the dirt on the panel and fuselage surfaces. Even though the surfaces had been cleaned, a film of fine dirt particles remained on both surfaces. As the robot walked along either surface, the dirt particles collected on the suction cups. As the cups attached to and released from a surface, they tended to slide a little, especially when the spine assembly was lowered to the surface. The dirt trapped on the bottom surface of the suction cups scored the surface slightly as the cup slid. A potential solution, suggested by a representative of an aluminum producer, is the replacement of the soft silicone suction cup with a harder rubber that would be less likely to trap dirt.

In a related problem, the eddy-current probe did not initially ride flat on the skin surface, compromising scan data. To compensate for this, the pressure used to deploy the sensor was

increased. As with the suction cups, dirt accumulated on the probe's surface, and when it was deployed, the probe also scored the skin surface.

The surface abrasion caused by the robot did not result in deep scratches to the surfaces and could easily be buffed away. However, this may not be acceptable to aircraft maintenance personnel and must be further investigated. The tendency to score an aluminum surface is a characteristic of all surface-walking robots. Dirty surfaces will be regularly encountered during routine inspections in a real environment, so this problem must be addressed before surface-walking robots can be routinely deployed in the field.

5. CONCLUSIONS

Through laboratory testing at CMU and field testing at the AANC in Albuquerque, New Mexico, the technical feasibility of the robot system has been demonstrated. Specifically, the robot was able to achieve the goals of:

- adhering to an aircraft fuselage
- walking over its surface
- acquiring eddy-current inspection data.

In an auxiliary experiment using another robot moving on an aircraft skin surface, video camera-based automatic alignment and navigation were demonstrated.

A significant development effort remains before this robotic inspection technology is suitable for operational deployment. Outstanding development issues include:

- improving the mechanical reliability and speed of the system
- reduction or elimination of the umbilical cable
- automation of many of the manually controlled operations

While an extensive redesign of the mechanical system will be required to obtain a commercial version of the robot, the existing robot provides an adequate platform to continue development of the control software for further automation of the inspection process. The integration of the video-based rivet detection algorithms with the robot control software and the enhancement of the robot navigation and control software are crucial to making this technology succeed and will be the focus of the next phase of the project. Once these issues are resolved, designing and building a new mechanical system to address the speed and reliability of the robot must be undertaken to commercialize the technology.

6. BIBLIOGRAPHY

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